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Translation of "Izmereniye soprotivleniya tela zvezdoobraznoy formy v sverkhzvukovom potoke pri chislakh M ≈6 i 8."
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MEASUREMENT OF THE DRAG OF A STAR-SHAPED BODY IN HYPERSONIC FLOW AT M ≈ 6 AND 8

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ABSTRACT: Experimental measurement of the aerodynamic drag of a conical body with a star-shaped cross section at Mach 6 and 8 together with a photographic analysis of the wake pattern behind the body. Experimental and theoretical data are compared for the drag of a cone and a star-shaped body. The results indicate that the overall drag of the star-shaped body is less than half as great as the drag of an equivalent circular cone. The jump pattern arising in the flow around the star-shaped body is analyzed and the flow between the points of the star is illustrated.

Results were obtained during the last few years which make it possible to get an idea about the optimum shape of a spatial body in hypersonic flow. It was shown [1-6] that bodies with star-shaped cross sections, with some limitations, have the lowest wave drag and remain optimal with respect to the total drag when the friction forces are [only] approximately taken into account. Here changing from an optimum body of revolution to a star-shaped body of equivalent volume and length makes it possible to reduce the drag several fold. These theoretical results, which were first obtained on the basis of Newton's drag law, were then verified by an exact solution [7] for bodies with shapes close to optimal. Subsequently detailed experimental studies were performed [8, 9] of the flow pattern between two lobes, which comprise an element of the "star", in a wide range of apex angles. These experiments have shown that the flow described by the solution [7] actually takes place between the lobes, it is stable, and the wave drag calculated on the basis of the pressure distribution at the surface of the body is manyfold lower than for the equivalent cone. These results, although promising, do not as yet give advantage to the star shape in practical use. The point is that the "star" has a very large streamlined surface, hence the effect of this reduction in drag can be offset by an increase in the frictional resistance. The above references to theory in which friction is taken into account is not convincing, since the friction estimates are highly approximate, while the actual flow is complicated by the presence of shock waves in the flow, with the possibility of a turbulent boundary layer, flow separation, etc. All these factors cannot be taken into account and a judgement about the drag of a "star" can be handed down only after direct measurement of the total force acting on a model in the flow. /94*

Below are described results of balance tests performed for a model of a "star" at $M_\infty \approx 6$ and 8. In addition to recording of forces, the flow pattern in the body's wake was photographed.

<u>1. Original data for computations and description of models.</u> We shall consider a class of star-shaped bodies with cross sections composed of straight-line segments. As was shown in [7], plane shocks, attached to edges and regularly intersecting are formed near such bodies. If we take as our starting parameters the angles α and γ

*Numbers in the margin indicate pagination in the foreign text.

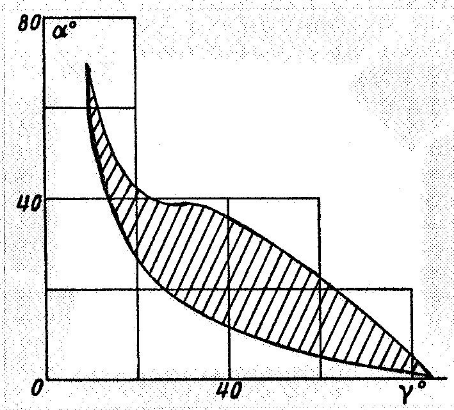

Figure 1

(notation follows that of [7]), which describe the shock position and angle π/n between adjoining lobes of the body with specified length, then they can be used to express the coordinates of all the characteristic points which define the geometry of the body.

However, it is known [8] that no solution exists for all the possible M_∞, α, γ and n, which makes it necessary to first determine the permissible range. In the case of $M_\infty = 6$, this range, constructed by referring to [8], is represented in Fig. 1. The studies were made for a model with n = 10 lobes. Parameters α and γ, within the permissible range (Fig. 1) were assumed to be $\gamma = 20°$ and $\alpha = 41°$. On design consideration the model length was taken as 95 mm.

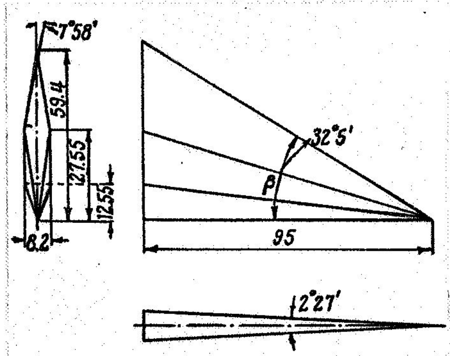

Figure 2

Using these values and formulas presented in [7] we /95 have determined all the cross sectional dimensions of the "star." The shape of the lobe together with the pertinent dimensions is shown in Fig. 2. The second model, which was taken as standard for comparison, was a sharp cone with an apex angle of $2\theta_\gamma = 37°$. A picture of this cone and of the "star" is shown in Fig. 3. The models have the same midsection areas (S = 31.5 cm²), length (L = 95 mm) and, consequently, the same volume.

2. Results of balance tests. These tests made it possible to obtain the magnitude of the total drag of the "star" and cone models.

The characteristic dimension used in calculating the total drag coefficient was the midsection area. The total resistance of the "star" in a range of the angle of attack from -2 to 3° for $M_\infty = 6.00$ are presented in Fig. 4. The sequence in which the angles of attack were varied is denoted by numbers 1–8. It can be seen from the graph that the zero setting angle of attack did not correspond to the true value $\alpha = 0$, since minimum resistance is obtained at $\alpha = -2°$.

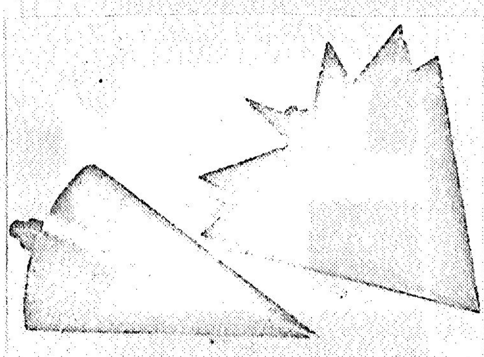

Figure 3

Figure 5 shows experimental and theoretical values of drag coefficients of both models for incoming flow velocities corresponding to $M_\infty = 6$ and 7.80. It should be pointed out that for the "star" these values of C (open circles) correspond to the angle of attack (in the test unit) of $\alpha = 0°$. The minimum value of C_τ. is designated by a square. For comparison the graph also displays experimental values of C_τ of the equivalent cone (black circles) obtained in the experiments described as well as in others. The theoretical values of C_τ for the cone were found from the expression $C_\tau = C_\tau^0 + C_\tau^1 + C_\tau^2$, where C_τ^0, C_τ^1 and C_τ^2 are the wave drag, base drag and friction drag, respectively. The wave drag is determined precisely from Kopal-type tables. The base drag

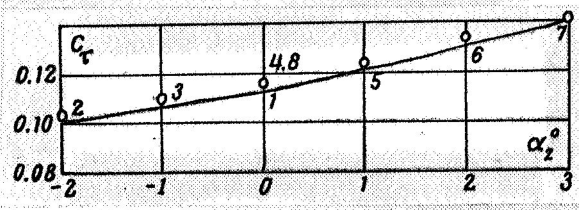

Figure 4

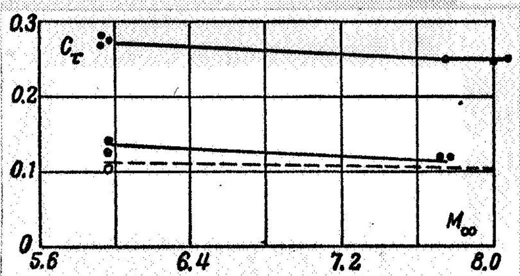

Figure 5

for the cone calculated by the standard method was found to be $C_\tau^1 = 0.035$ for $M_\infty = 6.00$ and $C_\tau^1 = 0.019$ for $M_\infty = 7.80$.

The friction drag was determined from the expression $C_\tau^2 \approx 0.05(C_\tau^0 + C_\tau^1)$. The total drag of the "star" is estimated in a similar manner. /96

The wave drag for the case of design conditions for flow past the "star" ($M_\infty = 6.00$) is known exactly and, according to [7], $C_\tau^0 = 0.064$. The base drag for the star is assumed equal to the corresponding value for the cone. The friction drag is found on the assumption that the flow past each lobe is the same as flow past a plate with a tapered leading edge. Then breaking up the plate into elementary strips and integrating, we get

$$C_\tau^2 = \frac{A_k S_n k^2}{S(k+1)(k+2)} R_L^{-1/k}$$

where S_n is the side-surface area of the "star" and S is the midsection area.

It was assumed in this derivation that the flow past each strip is independent, corresponding to that of a plate of the same length. For a laminar boundary layer k = 2: a = 1.32 c, where c is the compressibility factor; c = 0.83 for M = 6.0 and c = 0.7 for M = 7.8; the laminar Reynolds number R_L was determined on the basis of the velocity at the outer boundary of the lobe's boundary layer past the shock and was related to the model length L.

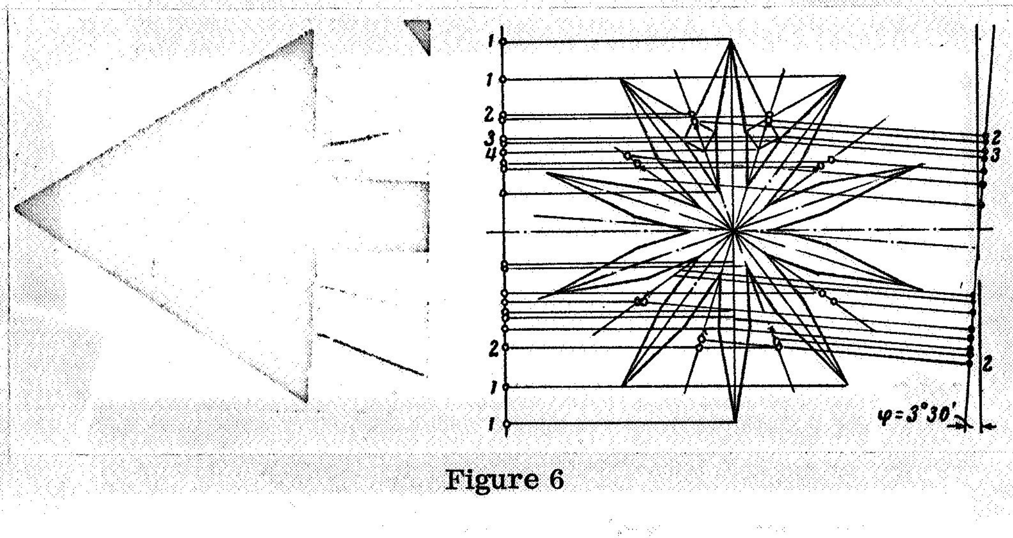

Figure 6

The calculated results are shown in Fig. 5 by dashed lines. For the cone-shaped body the dashed line is close to the experimental curve, drawn as a solid line, thus showing that good agreement is obtained with experimental data. It should be noted that these calculations serve as estimates [only] since a part of the quantities used in them is described by semiempirical theories. It is noteworthy that in Fig. 4 the minimum experimental value of the drag is somewhat lower than the theoretical. It is possible that this is a result of overestimating the base drag in the above calculations, since the base of the "star" has a substantially different shape than the base of the cone.

As a whole the balance tests show that the total drag of a star-shaped body is by more than two-fold lower than the drag of an equivalent round cone. This results in incomplete agreement with predictions of a previously controversial theory [9].

3. Studies of the flow spectrum. Let us now consider the system of shocks which are produced in a flow past a star-shaped body. As was shown in [10], there exists in the wake of the model a flow region which corresponds fully to the structure of the flow between the lobes and is not distorted by disturbances of the trailing edge. The flow pattern between the lobes is shown in Fig. 6. The open circles show positions of shocks for an angle of roll of $\varphi = 0$, while the black circles show these positions for $\varphi = 3°30'$. The photograph shows the line of shocks 1, attached to the forward edges of the lobes, and bright lines 2 of intersection between these shocks inside the flow region. According to theory, the points of intersection of the shocks should pass through points marked by /97
crosses. However, they are situated higher, which, apparently, is due to the fact that the actual Mach number obtained in the experiment was lower than that assumed theoretically, as well as due to viscosity. Lines 3 correspond to traces of shocks reflected from the walls, while lines 4 may represent shocks reflected from the walls, as well as lines of secondary shock intersections. In [10] the points of reflection of secondary shocks from wing surfaces were situated above the points of deflection of the inner wing surfaces. The corresponding points of reflections for the "star" at hand were also situated somewhat above the point of deflection. Thus the actual hypersonic flow with a Mach number differing from that theoretically assumed, a moderate angle of attack, and in the presence of viscosity is close to that of a pattern with regular intersection of shocks which is supplemented by a system of weak shocks reflected from the walls.

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